Extreme ultraviolet interferometry: at-wavelength testing of optics for lithography

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INTRODUCTION

Extreme ultraviolet (EUV) lithography is a promising and viable candidate for circuit fabrication with 0.1-micron critical dimension and smaller. To achieve this end at 13-nm wavelength, nearly diffraction-limited, multilayer-coated, near-normal-incidence reflective optical systems with 0.1 numerical aperture are required [1]. The suggested wavefront aberration tolerance for these sophisticated, all-reflective systems, composed of aspherical elements, is only 0.02 waves RMS, or 0.27 nm [2]. This places extremely high demands on the fabrication of EUV mirror substrates and multilayer coatings and even higher demands on the metrology tools required to characterize them.

The EUV wavefront is determined by the geometric figure of the mirror surfaces and by the properties of the molybdenum/silicon multilayer coatings, which are deposited across mirror areas of several square centimeters. While advanced visible-light interferometric techniques possessing the required measurement accuracy are being developed [3], optical aberrations arising from multilayer coating defects and thickness errors are measurable only at the EUV operational wavelength. Furthermore, it is widely agreed in the lithography community that final alignment and qualification must be performed at-wavelength in order to successfully predict the imaging performance of an optical system. These factors motivate the development of high-accuracy EUV wavefront-measuring interferometry.

A NOVEL EUV INTERFEROMETER DEVELOPED FOR HIGH-ACCURACY

Researchers from LBNL’s Center for X-Ray Optics have built a prototype EUV phase-shifting point-diffraction interferometer (PS/PDI) [4] at ALS Beamline 12.0.1.2. This interferometer incorporates major enhancements over its predecessor, a conventional point-diffraction interferometer [5] implemented for the measurement of diffractive Fresnel zoneplate lenses at 13-nm wavelength.

The PS/PDI is a nearly common-path interferometer that incorporates pinhole diffraction to generate spherical reference wavefronts of extraordinarily high accuracy. Light from an undulator beamline is focused through a pinhole spatial filter to produce a coherent spherical wavefront to illuminate the optical system under test. A coarse grating beamsplitter placed before the test optic divides the beam into multiple diffractive orders that are brought to spatially separated foci in the image-plane. One beam, the *test* beam, containing the aberrations of the test optical system is allowed to pass through a large window in an opaque mask placed in the image-plane. A second beam, the *reference* beam, is spatially filtered by a pinhole smaller than the diffraction-limited resolution of the test optic, and becomes a second spherical wave. These two beams overlap and produce an interference fringe pattern that is detected by an EUV CCD detector. The interference pattern may be interpreted as a coherent comparison of the aberrated test beam, and the nearly-perfect spherical reference beam. The fringe pattern thus reveals the aberrations in the test optic. Translation of the grating beamsplitter is used to introduce a controlled relative phase-shift between the test and reference beams. This design is optimized for much higher efficiency than the PDI and introduces improved measurement accuracy through its phase-shifting capability.

10X SCHWARZSCHILD OBJECTIVES

The focus of the interferometry research in 1997 was on the measurement of two prototypical EUV lithographic optics, and on the characterization of the performance of the interferometer itself. The reflective, near-normal-incidence, 10x-demagnification Schwarzschild objectives consist of two nested-spherical mirrors. Illumination of an off-axis sub-aperture of 0.08 numerical aperture, these systems are designed for 0.1-µm resolution over a 400-μm^2 field-of-view. The configuration of the interferometry endstation and the important optical components are shown schematically in Fig. 1. The EUV beam illuminates the optic from below reproducing the way it is used in a prototype EUV lithographic system at Sandia National Laboratory [6].

Of the two different optics tested, the measured wavefront aberrations are on the order of 1 nm, or 0.08 waves at 13.4-nm wavelength. A typical interferogram (interference fringe pattern) from one of the optics is shown in Figure 2. Analysis reveals the nearly-diffraction-limited wavefront phasemap shown.

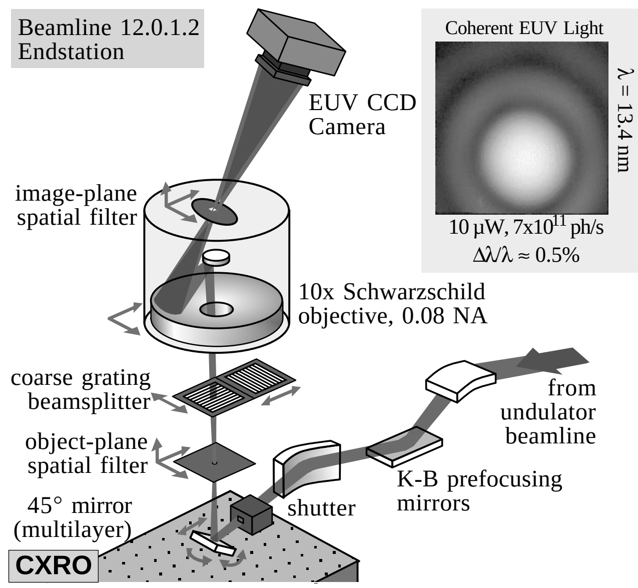

Figure 1. Configuration of the EUV interferometry endstation for the measurement of an EUV 10x Schwarzschild objective. The test optic is designed for use in a prototype EUV lithography system where it is held in a vertical orientation. Interferometric testing is therefore also performed with illumination from below.

INTERFEROMETER CHARACTERIZATION

During 1997, a large number of experiments were conducted to measure the precision and accuracy of the interferometer. Literally thousands of individual interferograms were recorded in the span of a few months. Repeatability tests all indicated measurement precision on the order of 1-2 angstroms in a variety of measurement configurations [7]. Each component of the interferometer was separately examined with *in situ* tests to evaluate its performance and identify potential systematic effects.

The most important function of interferometric optical testing is the prediction of imaging performance. To verify the accuracy of the wavefront measurements, the 10x objectives were used in a series of resolution test pattern printing experiments at Sandia National Laboratory. The results provided excellent agreement between the predicted and the measured performance.

Other tests demonstrated the first direct observation of chromatic effects related to the reflective properties of multilayer-coatings [8]. Figure 3 shows how the measured wavefront changes as the

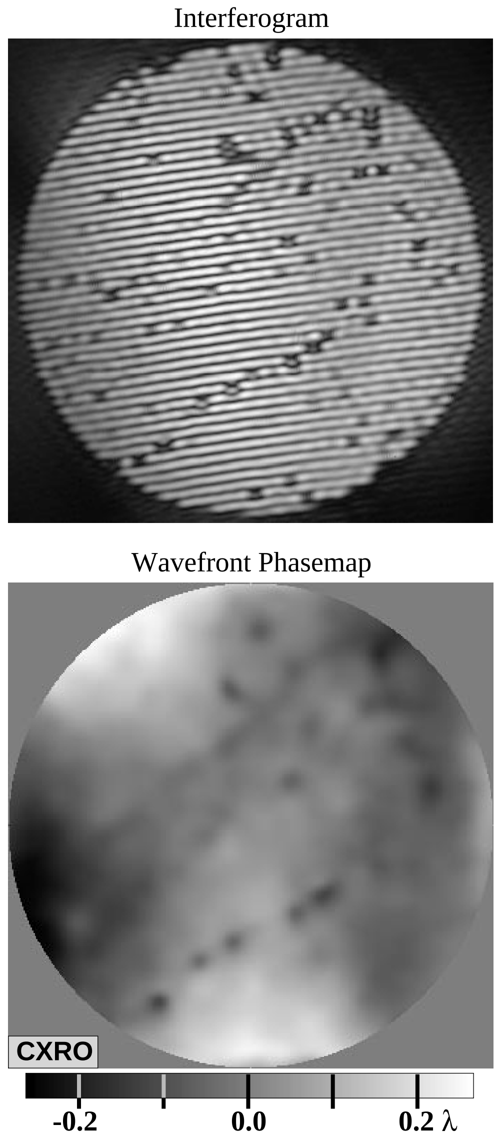

Figure 2. An interferogram recorded during the measurement of an EUV 10x Schwarzschild objective reveals small wavefront aberrations. These aberrations describe the combined effect of the surface figure of the combined two-mirror system plus the phase-effect introduced by the multilayer mirrors.

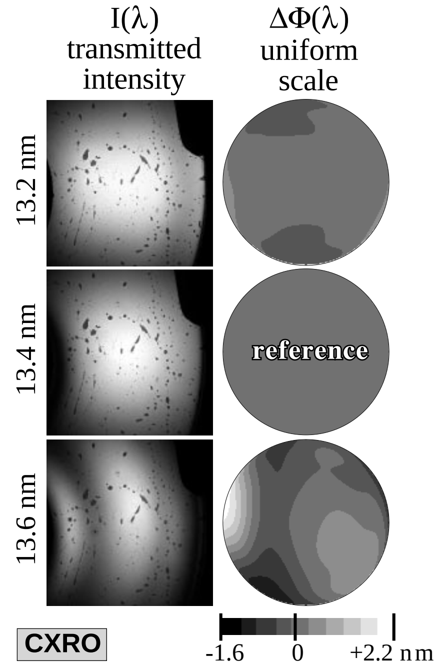

Figure 3. Evidence of the chromatic properties of multilayer mirrors is clearly visible in both the transmitted intensity, and in the changes in the EUV wavefront relative to the 13.4-nm wavelength measurement.

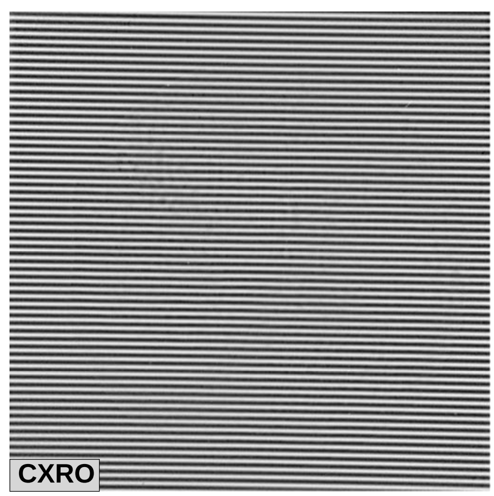

Figure 4. A nearly-perfect interference pattern from a two-pinhole experiment, covering the 1-square-inch area of a CCD detector. Small variations in the fringe contours reveal systematic measurement errors are below l/250, or 0.5 Å, in the PS/PDI.

wavelength is tuned from 13.2 to 13.6 nm. The interferometer is capable of probing the multilayer properties in ways that are invisible to measurements performed using visible light.

To investigate the accuracy of the interferometer, and probe the magnitude of systematic measurement errors, a series of two-pinhole experiments was performed [9]. Similar to Young's famous experiment, both the test and the reference beams were filtered by the tiny image-plane pinholes. A typical interferogram from these measurements is shown in Fig. 4. It was revealed that for pinholes below 120-nm diameter, reference wavefront accuracies below $\lambda/100$ waves

(1.3 Å) are achievable. Furthermore, for pinholes of 100-nm diameter, the reference wavefront quality is λ/250 RMS (0.5 Å) on average. Since the pinhole functions as a spatial filter for the aberrated test beam, it is hoped that as higher quality-optics are tested, the wavefront quality can be further improved.

REMARKS FOR FUTURE WORK

With a verified measurement accuracy and precision well beyond the current state-of-the-art in optical fabrication, this interferometer will serve as an important measurement tool in the development of advanced EUV optical systems.

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